INCIDENT

Aircraft Type and Registration:	Embraer EMB-145EP, G-RJXG
No & Type of Engines:	2 Allison AE3007/A1/1 turbofan engines
Category:	1.1
Year of Manufacture:	2001
Date & Time (UTC):	25 September 2001 at 1411 hrs
Location:	On approach to Manchester International Airport, Manchester
Type of Flight:	Public Transport
Persons on Board:	Crew - 4 Passengers - 17
Injuries:	Crew - None Passengers - None
Nature of Damage:	Light fuselage skin and rivet burns. Heat damage to right wingtip
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	42 years
Commander's Flying Experience:	8,919 hours (of which 905 were on type) Last 90 days - 117 hours Last 28 days - 19 hours
Information Source:	Aircraft Accident Report Form submitted by the pilot and further enquiries by the AAIB

Synopsis

The aircraft was carrying out a scheduled flight from Aberdeen to Manchester. The commander, who was the handling pilot, reported that during the flight the weather radar was displaying weak returns of cumulonimbus cloud activity, but he manoeuvred the aircraft in order to avoid the affected areas, primarily by visual means.

He accepted radar vectors to position the aircraft downwind for the landing runway. Just as the aircraft entered cloud, a lightning strike occurred. The commander subsequently reported that there was neither turbulence nor significant precipitation at that time. Recorded data indicated that the aircraft was close to FL70 at the time with a low thrust setting.

The first officer informed the commander that he had observed a left engine over-temperature indication. Within 5 to 10 seconds of the strike, both crew members noted that the left engine operating parameters were decreasing rapidly. They were not aware of any warning or caution indications at the time.

A distress call was broadcast and checklist procedures for both engine failure and single engined approach were carried out. An uneventful single engined landing then took place at 1415 hrs.

Aircraft damage

Subsequent examination of the aircraft revealed evidence of lightning strike damage on the left side of the fuselage. This extended from just aft of the flight-deck windshields to a point above the junction of the wing trailing edge and the fuselage. The evidence took the form of marks on longitudinal skin joints and a row of rivet burns, initially low down on the fuselage side, then continuing aft at a higher level above the wing. Considerable lightning damage was evident on the composite right wing tip fairing.

The left engine was subjected to a complete borescope examination and the two Full Authority Digital Engine Control (FADEC) units were replaced. Engine ground runs were carried out satisfactorily. The engine then performed normally during subsequent flights. The FADEC units were returned to their manufacturer for examination. They were found to be undamaged and no fault codes were found to have been recorded. When rig tested they operated in accordance with their performance specifications. They were also returned to service with no subsequent abnormalities being noted.

Description of the FADECs

On the EMB-145, each engine is controlled by one of two FADECs, designated 'A' and 'B'. All signals between each FADEC and its respective engine and between the FADECs and the aeroplane are completely duplicated. The FADECs are interconnected by dedicated Cross-Channel Data Links (CCDL) which are used to transmit engine data and FADEC status between the two FADECs on each engine. Each FADEC is also connected to one of the two FADECs on the opposite engine via an inter-nacelle data bus. Through this bus, the FADECs communicate the information necessary to implement thrust reverse interlock and Automatic Take-off Thrust Control System functions.

Each FADEC receives command signals from the Control Pedestal and from the Powerplant Control Panel and sends a command signal to the Fuel Pump and Metering Unit (FPMU) torque motor, which meters the fuel flow to the engine in order to reach the fan spool speed calculated by the FADEC thrust management section (N1 REQUEST). In addition, the FADECs command the Compressor Variable Geometry (CVG) actuators in order to optimise the compressor efficiency and compressor stall margins.

In normal operation, the engine control logic receives a fan speed request (N1 REQUEST) from the thrust management logic and controls the engine fuel flow and CVG to obtain the required engine steady-state and transient response. The FADEC contains a schedule of CVG position versus corrected gas generator speed (N2) that has been selected to provide the optimum compressor efficiency for steady-state conditions and adequate stall margins during transients. The FADEC senses the CVG position and commands the CVG actuator to maintain the CVG position at the desired setting.

The Air Data Computers (ADCs) provide the ambient and airspeed data used by the FADECs to calculate the maximum available thrust (N1 TARGET) for each selected thrust-rating mode. Each thrust lever modulates engine thrust linearly between the IDLE and THRUST SET position.

The two FADECs of each engine alternate in the powerplant control and while one controls the powerplant, the other remains in standby mode. The standby FADEC monitors all inputs, performs all computations, and performs built-in-test and fault detection, but the output drivers (fuel flow and CVG control), which command the engine, are inactive.

Transfer from the active FADEC to the standby FADEC may be accomplished automatically, in response to a detected fault, or manually, through the FADEC Selector Knob, located on the overhead panel.

If N2 reduces to below 53.5%, the active FADEC will initiate a shutdown sequence on the engine to protect it from damage. There is, however, no communication of this condition, via the inter-nacelle data bus, to the FADECs on the opposite engine so, potentially, it is possible that the FADECs controlling both engines could signal shutdowns independently and simultaneously.

The engine control logic incorporates engine protection logic to protect the engine from damage due to exceedences of speed (N1 & N2) and Inter Turbine Temperature (ITT) limits. There is a surge avoidance fuel flow schedule built into the FADEC logic which is intended to avoid rapid transients and assist in the restoration of steady compressor flow conditions and permit the engine to accelerate and return to the desired operating condition following a compressor stall; this schedule is not, however, intended to provide active surge recovery. The FADEC also has an auto re-light function which activates the ignition system whenever a flameout is detected by the FADEC and N2 is higher than 53.5%, provided that the Ignition selector knob is set to 'AUTO'.

Flight Data Recorder (FDR)

Examination of FDR data, supplied via the aircraft manufacturer, showed that the thrust lever angle of the left engine had remained steady for some 9 to 10 seconds with very slightly varying fuel-flow, when a slight drop in both low pressure (N1) and high pressure (N2) spool speeds occurred. At this point there was a sharp, but limited rise in fuel flow and a considerable, rapid, rise of inter-turbine temperature (ITT); the spool speeds, however, continued to decay rapidly.

About two to three seconds later, the fuel flow reduced sharply and the ITT stabilised briefly before rising again, but more slowly than before. About four seconds later, ITT peaked at 965ºC and, as it did so, the fuel flow reduced further. About two seconds later, ITT began to reduce increasingly quickly and the fuel flow rose rapidly but briefly to a high value. There was no recorded rise in ITT in response to this increase in fuel flow, which then reduced rapidly to a very low figure before ceasing completely. Both spool speeds continued to decay at reduced rates throughout this period.

FADEC 1A was recorded as having been in control of the left engine at this time and is presumed to have been so throughout the incident. It detected no internal faults and no master warning was being generated although a brief period of Master Caution was evident immediately after the maximum fuel flow figure was recorded. The CVG vane position was not recorded.

Interpretation of engine related FDR data

It could be seen that, initially, the FADEC units were operating normally, such that the fuel flow was varying in accordance with its normal mode, controlling fan speed (N1) in response to throttle movements. During flight, either in turbulence or with varying airspeed, short period changes in intake conditions cause corresponding changes in fan loading. Varying fuel flow values are commanded to compensate for this effect, preserving a steady N1.

The initial engine behaviour from the point where N1 and N2 reduced, without a throttle command, believed to be immediately after the lightning strike (see 'Recorded lightning strike data'), was consistent with a compressor stall. It is believed that the spool speeds reduced, initially, as a result of the loss of mass flow through the engine brought about by adverse intake conditions caused principally by the aero-thermal effects of the lightning strike and that these conditions initiated a compressor stall.

The recorded limited increase in fuel flow at the point when the spool speeds started to decrease was an expected response to restore the selected speed, consistent with the inbuilt surge avoidance law. The ITT then appears to have increased as a result of this rising fuel flow and the decreasing mass-flow of air resulting from the steadily decreasing spool speeds, evident from the traces. It is also possible that mass flow was further reduced by aero-thermal effects of the lightning on the inlet conditions. The fuel flow then decreased sharply to a lower steady figure for about 3 to 4 seconds, which was consistent with the ITT limiter coming into operation at 948ºC. This steady fuel flow was that normally scheduled to allow the engine to operate well clear of the surge line but under the conditions prevailing did not allow it to stabilise and recover.

However, the ITT continued to rise, indicating a persisting surge condition, to its peak recorded value, at which point the fuel flow was further reduced, as a result of the ITT reaching the maximum permitted figure, to prevent turbine overheat damage.

Following this the ITT fell, briefly permitting the fuel flow to be increased in order to attempt to restore the spool speeds. However, since these speeds continued to decay the automatic shutdown facility intervened when N2 passed below the minimum scheduled figure (53.5%). It has been demonstrated that the engine cannot recover from speeds below 53.5% and the FADEC acts on the assumption that a major mechanical or structural defect may have occurred in the engine and shutdown is commanded to prevent additional engine damage or hazard to the airframe.

Final fuel shut-off was commanded approximately 11 seconds after the onset of the event. The flow rate then took 4 seconds to decrease to a very low value before ceasing totally.

The fact that FADEC 1A was recorded as being in control indicates that it remained so throughout the incident with FADEC 1B in standby mode. This, together with the fact that no fault was detected on FADEC 1A by the recording system, confirmed the subsequent post incident examination and testing of the FADEC units by the manufacturers, which found no faults.

Since post-incident testing and examination of the engine revealed no mechanical damage which was likely to have made it prone to surging, the only reasonable explanation for the initial reduction of N1 coincident with the increase in fuel flow is a disruption of the intake airflow. The subsequent continuing reduction in spool speeds, which was consistent with the fuel flow scheduled by the FADEC logic not being designed to re-establish surge–free operation, led to an automatic engine shut-down.

The automatic shut-down was the logical consequence of the FADEC control laws responding to the variations in engine speeds and temperatures recorded on the FDR. In particular it appears that the reluctance of the ITT to reduce, prevented the FADEC from restoring acceptable running conditions in the engine in the 11 seconds between the first indications of the incident and shut-down. It is probable that the aero-thermal effects of the lightning discharge, alone, were sufficient to initiate this event. It was considered that the continuing inability of the FADEC to be able to restore stable running conditions could be consistent with either, the effect of persisting disrupted intake airflow, the effects of the very hot, low density plasma passing into the engine or the large static charge associated with lightning discharges affecting the inputs to the FADEC, particularly the temperature sensing. Although the presence of a high static charge has been observed to affect temperature sensing in non-aeronautical electronic control systems, the engine manufacturer had conducted tests to validate the temperature sensing capability under such conditions.

The damage evident on the outside of the aircraft suggests a longitudinal distribution of lightning effects. It is thus reasonable to expect that such a longitudinal effect extended well forward of the aircraft, allowing the path of the engine intake to translate within a column of air through which the lightning discharge had also passed. The aero-thermal effect of such a strike, although not fully understood, is known to be potentially detrimental to intake flow conditions.

The engine manufacturer reviewed the recorded data and pointed out that the software in use at the time of the incident did not contain any compressor stall detection and recovery logic and that the engine and control system had responded as expected.

The engine manufacturer has considered developing surge detection logic for the FADEC of the AE3007A engine as it could minimise or eliminate the possibility of the engine suffering adverse reaction during any future lightning strike. However, at the present time it is considered that the technical complexity involved and risk of false surge detection inherent in such logic outweighs the established risk of suffering an in-flight shutdown as the result of a surge.

Recorded lightning strike data

Data was obtained from a lightning location system covering discharges in the general area of the incident, during the time period in question. The detection system that was utilised recorded the signatures of lightning strikes over a wide area and therefore did not guarantee to detect all strikes in any particular defined locality. A second database, listing strikes detected by an instrumentation system operating on a different principal, was also utilised. This system is designed specifically to detect only cloud to ground strikes and is optimised to cover a more limited area centred on the United Kingdom.

One isolated recording of lightning activity was detected by the first system at a time of 1408:16 hrs, at a position approximately 17 km north-northwest of Manchester Airport. Three cloud to ground strikes were recorded by the second system, all at least 23 km from Manchester Airport, during the period between 1400 hrs and 1408 hrs. These were all recorded as being of low power. Neither of the three cloud to ground strikes was detected by the first system and the strike recorded by that system was not recorded by the second (dedicated cloud to ground) system.

From the above data it appears most likely that the aircraft encountered a relatively low power cloud to ground lightning strike at 1400 hrs.

Significance of lightning damage

The physical damage to G-RJXG was limited to the structure. Both metal and composite materials were affected, the latter more dramatically. No ‘secondary’ damage was reported (ie to wiring or avionics). No physical engine damage occurred. The immediate effect on the aircraft was not judged to be hazardous. Loss of thrust from one engine did not result in any significant handling problems, as it was within the normal experience of recurrent crew training for dealing with non-normal procedures.

Other information

Another lightning event had occurred to another EMB-145 in April 2001, which had resulted in a pilot shutting down an engine due to high indicated ITT. This event occurred in France and the engine manufacturer was aware of it. The engine manufacturer's investigation concluded that the lightning strike had induced aero-thermal disturbance to the engine inlet which resulted in an engine stall.

No further similar occurrences on the EMB-145 are recorded on the UK CAA database. With this fleet having operated a total of some 6.2 million engine hours at the time of this incident, (now about 14 million) there is no immediate concern that the lightning strike/engine stall phenomenon is statistically prevalent. However, data supplied via the aircraft manufacturer, obtained during their investigation, revealed that some background data existed on apparently similar events occurring to other types.

A study of twin aft-engined commercial aircraft revealed that fuselage diameters ranged from approximately 5 ft for typical small business jets to nearly 11 ft for aft-engined airliners, such as the DC-9/MD80 series. The EMB-145 fuselage diameter is 7 ft 5 in, thus placing it near the middle of the range considered. Additionally, there are some twin engined combat aircraft types, with forward fuselage side engine intake configurations, which have fuselage widths and lateral intake spacing no greater than those of the small business jets.

It is understood that a survey was carried out involving forty aircraft lightning strike events during the 1970s. This covered Learjet, Cessna Citation and HS 125 models, which have fuselage diameters ranging from about 5 ft 6 in to 6 ft 4 in and, consequently small lateral spacing between their engine axes. Twenty of these reportedly resulted in engine flame-outs, most being re-lightable. One, of unknown type, suffering a double flame-out at 35,000 ft. A number of events were also reported on military aircraft, such as F111 and F4 but the severity of the latter events is not known.

A North American NA 265-80 (Sabreliner) business jet type, which has a fuselage diameter of approximately 5 ft 9 in, suffered a fatal accident in the USA after a lightning strike event at night. This had led to a double engine flame-out, followed by progressive loss of battery power (accelerated by failure to carry out electrical load-shedding), which prevented a re-start of either engine. The engine type was not FADEC equipped.

Expertise on lightning behaviour and engine behaviour subsequent to a strike

An opinion was sought from the lead research specialist within the main test facility in the UK, devoted to lightning testing of aircraft structural and systems components. In his view, lightning conditions similar to those encountered by this aircraft presented a significant risk of a double engine flame out on the aircraft type (ie aero-thermal effects disrupting the intake flows of both adjacently mounted engines). The view of leading lightning specialist in the USA was that a risk existed of lightning effects sweeping longitudinally down both sides of a narrow fuselage and that this could, therefore, affect the intake flows of both engines of narrow bodied aircraft, where the engines are necessarily mounted close to the fuselage sides (ie typical of many combat aircraft and all aft-engined business jet and airliner types).

A significant risk was thus considered to exist that a single strike could cause both engines to flame-out as a result of aero-thermal effects, with potentially catastrophic consequences. The specialist in the USA made the point, however, that this effect appeared to be most prevalent on aircraft with narrow fuselages. Although it appears that the 'narrower' aircraft may be more at risk, insufficient data exists to assess the relative risk of double engine flame-out to types such as the EMB-145 compared with 'wider' and 'narrower' aircraft but statistics suggest the risk is very low.

It is relevant to note that most FADEC equipped engines have surge protection logic, with the capability of automatically shutting down engines in circumstances described above, whereas engines with more traditional fuel control systems, upon which more data is available, do not have this feature. The latter group of engines, the majority in service, are more likely to suffer transient over-temperature conditions as an indirect result of a lightning strike, but may stand a greater chance of continuing to run thereafter since shut-down is primarily in the pilot's control.

In practice, lightning strike damage to aircraft does occur, both in the UK and elsewhere. Unfortunately, however, reliable data on lightning events is difficult to obtain, particularly when little or no physical damage has occurred. In this instance, the physical damage presented no identifiable hazard.

Only two reports of lightning-induced engine flame-outs on other types were found on a UK database and both of these events produced physical damage and/or component failures, which in turn led to the power losses. It would therefore seem that aero-thermally induced engine flame outs are rare in the UK. The low population of narrow fuselage, twin aft-engined aircraft, compared with that in North America, makes the absence of any data on this class of aircraft understandable.

The fact that two instances of lightning induced engine auto-shutdown have occurred to EMB-145 aircraft during a short period, however, indicates that repetitions might be expected. The recorded lightning data for this event suggests that this strike was not in the higher power category, so it would appear that such an effect does not require unusually powerful strikes for it to occur. The EMB-145 fleet is relatively new and has progressively increased in number over recent years, so a greater number of aircraft are now potentially vulnerable. However, since 1998, in UK airspace there have been 49 instances of lightning strike on EMB-145 aircraft; none since the subject strike has resulted in an in-flight engine auto-shutdown.

Engine restart considerations

Study of the recorded data on engine behaviour during this incident indicates that within 20 seconds of fuel shut-off being automatically commanded by the FADEC, N2 had decreased to a figure below the 10% minimum required for a windmill start, according to the emergency re-light procedure for the type. The published engine re-start envelope confirms that when operating below 10,000 ft an APU Bleed Air assisted start is required if the airspeed is below 220 kt; the 'Engine Failure/Shutdown' procedure has the appropriate step of 'APU (if serviceable) -- Start'. Since the commander did not report any abnormalities when performing this procedure it must be presumed that the APU was both available and started in this instance.

Should a double engine flame-out have occurred in this case, it is clear that the APU would have been required to be started prior to its use to assist re-starting of the first engine, with a consequent considerable loss of altitude before a re-start could have been achieved. Even from

FL70, it was considered that attempting to enter the unassisted re-start envelope by diving the aircraft was not a viable option. Clearly, had a double engine flame-out resulted from a lightning strike later in the approach, there may have been insufficient altitude to achieve both APU and one main engine start.

In April 2004, the CAA published an Aeronautical Information Circular (AIC 29/2004) concerning lightning induced engine malfunctions, specifically referencing this incident but not confining its applicability to this aircraft type, alone. The Circular concluded with two recommendations, the second of which recommends that operators review their procedures and to consider starting the APU, when available, before entering areas where the potential for lightning strikes exists.

There are however, two considerations which must be taken into account when looking at this possibility. The first is that, since the APU intake is likely to be within the affected aircraft zone if a double flame-out caused by a lightning strike occurs, the probability exists that the APU itself may be similarly affected and flame-out. If the implications of this incident are followed, it is possible that re-starting the APU may also be problematic. The second consideration is that the APU is an allowable deficiency for takeoff on this aircraft type specifically; this condition is applicable to other aircraft types which may need to be considered. Although it is clear from experience, that the statistical possibility of a double flame-out is extremely low, the acceptability of having the APU as an allowable deficiency is questionable when certificating an aircraft type which needs pressurised air for main engine starting.

With this deficiency classified as allowable, consideration may need to be given to the procedure to be followed if engine flame-out due to lightning occurs. In this instance, the crew appears to have accepted the loss of the engine and proceeded to an uneventful single engine landing. During the descent before landing, however, the aircraft remained vulnerable to a second flame-out resulting from another strike. Even with the APU available, they would have had a decreasing time in which to start the APU to assist main engine starting; without an APU available, a forced landing, in this case in a predominantly urban area, would have become inevitable.

Whilst accepting that the engine auto-shutdown occurred at a time of increasing workload for the crew, it might have been prudent to attempt to restart the engine as soon as possible, as the 'Engine Failure/Shutdown' procedure suggests and leave it at idle power if it could be started. Although the section of the Operations Manual related to 'Lightning' suggests attempting a restart, it qualifies this by stating 'dependant on the phase of flight' and does not indicate which stage of flight is considered critical. It is considered that flight at relatively low altitudes is more critical, particularly in Terminal areas.

Safety Recommendations

The FADEC logic had, by design, no surge recovery features and the surge prevention logic was unable to re-establish stable running conditions during the length of time which passed between the lightning strike and the eventual auto-shutdown of the left engine. The forward movement of the aircraft over the useful time period in question (probably about 0.5 km over 5 to 6 seconds) should have carried it clear of any air directly affected by the lightning strike and thus restored the availability of acceptable intake conditions. That the engine did not recover implied that poor airflow conditions may have persisted within the intake, the engine or both, or that the scheduled fuel control inputs made were optimised to restoring demanded power rather than ensuring that stable running conditions were obtained before restoring set power.

The engine manufacturer has considered the possibility of installing surge recovery logic in the FADEC but believes that, at this time, the risks outweigh the benefits.

Although statistically small, there is a potential hazard of a lightning strike affecting both intake airflows on narrow body aircraft equipped with twin fuselage mounted engines, with the associated potential for a double engine flame-out and the following recommendations are therefore made:

Safety Recommendation 2005-094

It is recommended that, in order to minimise the risk of uncommanded shut-downs, EASA, FAA and the Centro Tecnico Aeroespacial (CTA) of Brazil in conjunction with aircraft and engine manufacturers should review and, if necessary, initiate appropriate research into the aero-thermal disruption of intake flow and other effects of lightning strikes on fuselage mounted turbine engines in order to establish whether there is a safety of flight issue that should be addressed by appropriate future rulemaking. They should also consider the application of any proposed rules to types currently in service.

Safety Recommendation 2005-095

It is recommended that, with advances in the technology which becomes available to them, Rolls-Royce Corporation continue to explore the potential to make modifications to the FADEC logic to enable the re-establishment of stable running conditions, after detection of a surge condition, before the FADEC attempts to restore selected engine power.

The minimum airspeed for unassisted air starts of the engines fitted to this aircraft type is 220 KIAS. Aircraft approaching to land in conditions where there is an increased risk of lightning strike would be vulnerable to double engine failure and potentially unable to re-start an engine whilst flying at low speed in a high-drag configuration. Therefore, it would be wise for approaches in such conditions to be conducted with the APU running or, at the very least, available. Consequently, it is recommended that:

Safety Recommendation 2005-096

It is recommended that, consideration be given by Embraer to amending the EMB 145 operating procedures and minimum equipment list to ensure that, in the event of an engine flame-out and continued flight in a zone with a high probability of lightning strikes, the supply of APU air for main engine starting remains available.